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Crossed Beam Energy Transfer in the NIF ICF Target Design

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In the National Ignition Facility (NIF) ICF point design[1,2], the cylindrical hohlraum target is illuminated by multiple laser beams through two laser entrance holes on the ends. According to simulations by LASNEX[3] and HYDRA[4,5] plasma created inside the hohlraum will stream out of the LEH, accelerate to supersonic speeds and then fan out radially. Inside the hohlraum, flows are subsonic. Forward Brillouin scattering can transfer energy between pairs of laser beams (0 and 1) if the following frequency matching condition is satisfied[6-13]:

$$\omega_0 - \omega_1 = (k_0 - k_1) \cdot V + | k_0 - k_1 | c_s \quad (1)$$

where $\omega_{0,1}$ and $k_{0,1}$ are the frequencies and wave-numbers of the two laser beams, V is the plasma flow velocity and c_s is the local ion sound speed. In the nominal case of equal frequency beams, this requires the component of the plasma flow velocity transverse to the bisector of the beam directions to be sonic, with the resulting transfer being to the downstream beam. In the NIF beam geometry, this is from the outer to inner cones of beams.

The physics of this transfer is the same as in beam bending[14,15]; the difference being that in the case of beam bending the effect is to redistribute power to the downstream side of the *single* beam.

Were significant power transfer to occur in the point design, the delicately tuned implosion symmetry would be spoiled[7,16]. To directly compensate for the transfer, the incident beam powers would have to be adjusted. The greatest vulnerability in the point design thus occurs at 15.2ns, when the inner beams are at their peak power and are at their nominal design power limit. In this situation, some other means of symmetry control would be required, such as re-pointing.

At 15.2ns, the envelope focal intensities of the outer and inner beams are approximately 10^{15} and $6.7 \ 10^{14}$ W/cm^2 respectively. There is little absorption or diffractive spreading of the beams in the crossing region, so these intensities are also representative there. The outer beams are at higher intensity, despite their lower power, because of their smaller spot-size required to clear the LEH at their steeper angle of incidence. The approximate locations of the crossing beams are shown in Fig. (1). There are four cones of NIF beams entering each LEH. The eight quads at 50° and 44.5° to the hohlraum axis are termed the outer beams; four quads at 30° and 23° form the inner beams. Each cone is arranged symmetrically around the hohlraum axis, staggered in azimuthal angle. Condition (1) is thus a constraint on the 3D plasma flow velocity that differs modestly, depending on precisely which pair of overlapping beams is considered. In order for the correct component of the flow to be sonic, the total flow in general will be supersonic. The potential resonant surfaces therefore lie outside the LEH.

Fig. (1) shows four beams and the component of the Mach Number (i.e. the velocity normalized to the local ion sound speed) appropriate for transfer between a typical inner-outer beam pair at 15.2ns, calculated by LASNEX. Note that the resonant surface fails to penetrate the beam crossing volumes. This should significantly mitigate beam power transfer. However, lack of exact resonance does not mean that power transfer cannot occur, only that it will be significantly reduced. In Fig (2), we plot the amplitude spatial growth rate for the forward SBS process, g, responsible for power transfer as a function of transverse velocity, for two plasma conditions bracketing those found in the crossing volume, given by:

$$g = \frac{1}{8}\left(\frac{v_0}{c}\right)^2 \frac{k^2}{k_0} \text{Im}\left(\chi_e (1+\chi_i)/(1+\chi_e+\chi_i)\right) \quad (2)$$

Here v_0 is the oscillatory velocity of an electron in the pump laser electric field, $k=k_0-k_1$ is wave-vector of the ion wave, and $\chi_{e,i}(k \bullet V, k)$ are the electron and ion susceptibilities. The peaks arise from the ion wave resonances. Their widths are determined by the ion wave (Landau) damping.

Except for a narrow jet of H/He along the hohlraum axis, the crossing volume consists of fully-ionized CH ablated from a coating on the LEH, applied to prevent hole closure. The curves in Fig.(2) are computed for this material. At the Mach 1 resonance, we see that the amplitude growth rates at resonance range from 6-12 cm^{-1}. However, the peak transverse velocities in the crossing region only reach 2-3 10^7 cm/sec, reducing these rates by an order of magnitude.

To quantify the expected beam to beam power transfer, for each outer-inner beam pair, the gain coefficient, g, from Eq. (2) was integrated along the inner beam path over the region of its intersection with the outer beam. Each beam was considered to have a uniform intensity over an elliptical cross-section. The resulting integrated linear gain G, was thus found as a function of ray position on the inner beam cross-section.

Fig (3) shows the result of one such calculation for the crossing of a 23° inner beam with its neighbor in azimuth 44° outer beam. For these calculations we used the results of a 3D HYDRA simulation to provided the plasma conditions at the 15.2ns time of interest. However, the azimuthal flows and variations in plasma conditions proved insignificant. Two dimensional simulations of this target would have been adequate for this purpose. The figure shows that the intensity gain, 2G, has a broad peak around 0.22.

It is thus clear that some account of pump depletion must be made to estimate the power transfer. This was done by using Tang's formula[17] on a ray-by-ray basis. The linear amplification exp(2G) was replaced by;

$$\exp(2G) \rightarrow (1+\beta)\exp\left(2G(1+\beta)\right)/\left(1+\beta\exp\left(2G(1+\beta)\right)\right) \quad (3)$$

where β is the incident ratio of outer and inner beam intensities. Correspondingly, the inner beam ray's powers are diminished by the factor $(1+\beta)/(1+\beta\exp(2G(1+\beta)))$.

Integrating this over the beam cross-section yields a prediction for the fractional power transfer, accounting for pump depletion, shown in Table (). Also include in the table are the corresponding results when the inner beams are red-shifted by 1Å and 2Å (at 1ω). These shifts put the ion waves further off-resonance, reducing transfer. The NIF is designed to have such a capability, so this would be a possible way to mitigate the effects of power transfer.

It is obvious to ask to what extent ion wave non-linearities could reduce their driven amplitude and consequently reduce transfer. In Fig (4) we show the ion wave amplitude as a function of transverse flow velocity for the conditions of Fig (). We see that dn/n~0.002 is typical of the ion wave amplitudes in the crossing region. This is too small for secondary instabilities, such as two-ion decay[10,18] to be excited. Likewise, nonlinear steepening, which is quadratic in the amplitude should be insignificant. Frequency shifts, created by ion wave trapping, a mechanism that has had some success in explaining experiments on *resonant* energy transfer[12,13] are predicted to be 1-2% of the ion acoustic frequency – insufficient to affect even resonant transfer, and presumably insignificant in the context of ion waves driven off-resonance. However, relatively little attention has been paid to the saturation of non-resonantly driven ion waves. Perhaps there are other mechanisms that are effective at these low amplitudes.

It is yet unclear whether these estimates are robust to possible changes in the NIF ICF target design. The predicted transverse velocities lie at the foot of the resonance curves of Fig. (15), so modest increases of the transverse Mach number in the crossing region would significantly increase the potential for beam power transfer. On the other hand, the plasma flow through the LEH resembles nozzle flow, in which case the Mach Number distribution outside the LEH would be highly insensitive to changes in the design. The flow would then be sonic in the LEH and accelerate with its geometrical expansion outside.

As a test of this hypothesis, we computed the flow of an ideal gas through a circular orifice by the method of characteristics.[19] The flow was taken to be sonic in the aperture and the ratio of specific heats was taken to be one, the isothermal limit. The temperatures and densities of the problem scale to those in the aperture, and the space scale of the flow is set by the diameter of the aperture, so there are no other free parameters in the problem. In Fig (5), we can see that the resonant Mach 1 contour from the aperture problem lies quite close that from the LASNEX simulation of the ICF point design (shown at 15.2ns), suggesting that the flow outside is indeed generic. The most obvious discrepancies near the region of interest are in the H/He jet near the hohlraum axis (the isothermal gas-dynamic model assumes a single gas species) and near the bottom edge of the LEH.

We could also expect to influence the power transfer by changing the composition of the LEH coating. The choice of CH for this purpose was somewhat arbitrary; other low-Z materials could be substituted. If the crossing region remains non-resonant, Beryllium might be a possible choice as it has weaker ion Landau damping and its ion acoustic response falls off thus more rapidly away from resonance.

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Figure Captions

Fig.(1): Schematic of crossing beams in hohlraums at the NIF and flow Mach number for the component of the flow velocity parallel to the beat wave-number of the crossing laser beams. The outer beams are dotted, the inner dashed.

Fig.(2) Crossed beam amplitude spatial growth rate vs. transverse velocity. Beam intensities are $1.0 \ 10^{15}$ W /cm^2 and $6.7 \ 10^{14}$ W /cm^2 .Plasma conditions are Te=4.4 (3.8) KeV, Ti=1.2 (0.85) KeV, Ne/Nc=0.027 (0.017) in H plasma for the upper (lower)curve.

Fig.(3):Spatial gain for transfer from a 23° beam to the adjacent 44° beam as a function of position in the 23° beam cross-section.

Fig.(4):Ion wave amplitude vs. transverse velocity. Beam intensities are $1.0 \ 10^{15}$ W /cm^2 and $6.7 \ 10^{14}$ W /cm^2. Plasma conditions are Te=4.4 (3.8)KeV, Ti=1.2 (0.85) KeV, N_e/N_c=0.027 (0.017) in CH plasma for the solid (dashed) curve.

Fig.(5): Contours of the transfer component of the flow Mach number from LASNEX (at 15.2ns) and isothermal steady state expansion theory vs. axial and radial distance in front of the LEH.
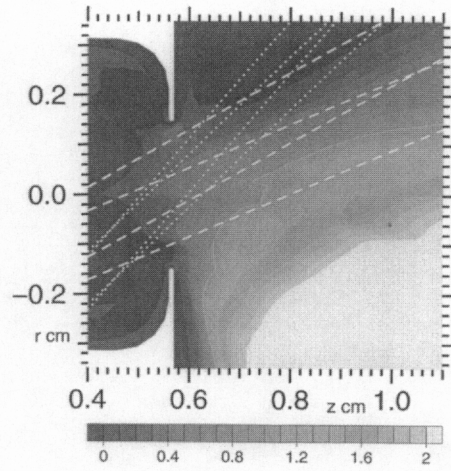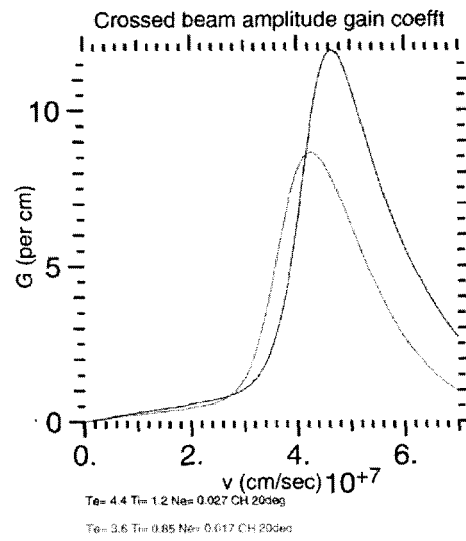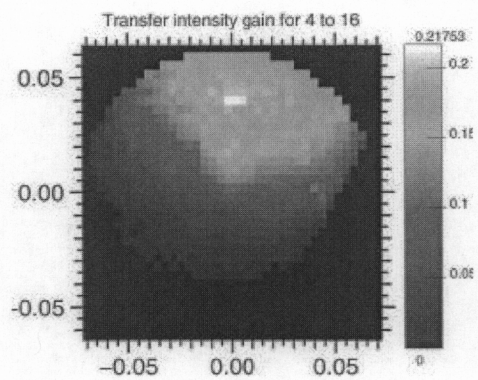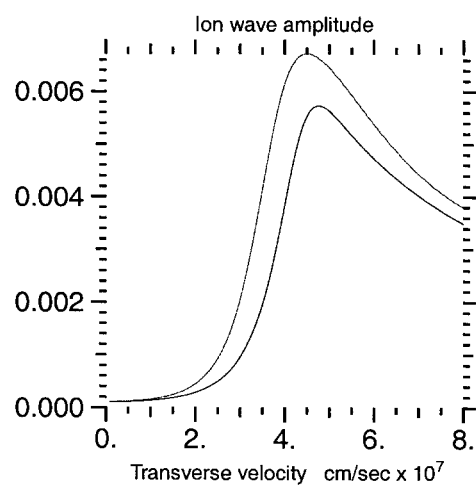
FIG 1

Crossed beam amplitude gain coefft

G (per cm)

v (cm/sec) 10^{+7}

Te= 4.4 Ti= 1.2 Ne= 0.027 CH 20deg

Te= 3.6 Ti= 0.85 Ne= 0.017 CH 20deg

FIG 2

Transfer intensity gain for 4 to 16

FIG 3

Ion wave amplitude

Transverse velocity   cm/sec x 10^7

FIG 4
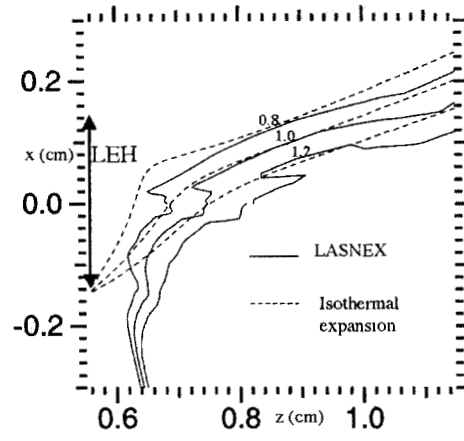
FIG 5

Beams	0Å	1Å	2Å
$23° \rightarrow 44°$	10%	5%	3%
$23° \rightarrow 50°$	6%	3%	2%
$30° \rightarrow 44°$	15%	7%	2%
$30° \rightarrow 50°$	25%	13%	6%

TABLE I: Predicted power transfer from NIF inner to outer beams at 15.2ns in the Scale 1.1 point design, with inner beams red-shifted by 0, 1 and 2Å